

# Multi-component decaying behavior on high-b-value diffusion-weighted MRI

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**Abstract**—This study reported the multi-component decaying behavior on high-b-value diffusion-weighted MR images. Signal intensity was measured in different regions of the brain. Results showed that gray matter and cerebrospinal fluid exhibited single exponential decaying characteristics while multi-component decaying behavior was observed in some white matter areas with complicated neural fiber orientations.

## I. INTRODUCTION

Diffusion-weighted MR imaging (DWI), in particular mapping of the diffusion tensors, has been proven useful in depicting neural fiber orientations by making use of the anisotropy of structure-restricted diffusion [1], [2]. Due to scan time consideration, mapping of the diffusion tensors is often performed with only two b values, on the order of 0 and 1000 sec/mm<sup>2</sup> in the human brain. On the other hand, during the development of many neurological disorders in human brain, alterations in the apparent diffusion coefficient (ADC) of water have been detected [3], [4]. So far, most studies performed with conventional MRI hardware report diffusion measurement in terms of a single ADC. In other words, the signal decay caused by water diffusion is assumed to be mono-exponential. With the advent of advances in hardware technology, high-b-value (>1000 sec/mm<sup>2</sup>) DWI is made feasible in clinical MR systems and it has been shown that the diffusion signal decay is no longer monoexponential under high b values [5].

In this study we report the investigation of the multi-exponential behavior observed on DWI with b values up to 3000 sec/mm<sup>2</sup>. We provide an explanation for this behavior and address the cautions in its applications.

## II. MATERIALS AND METHODS

### A. Image Acquisition

Transaxial echo-planar diffusion-weighted images of the brain were acquired from healthy volunteers using a 1.5T system (General Electric Signa Horizon, Milwaukee, Wisconsin) with multiple b values of 0, 500, 1000, 1500, 2000, 2500, and 3000 sec/mm<sup>2</sup> (TR/TE=4700/118, in-plane resolution 1.2x2.5 mm<sup>2</sup>). Diffusion-weighted gradients were applied along three orthogonal directions (superio-inferior, antero-posterior, and right-left) for all b values. Signal intensity measured in different regions of the brain was fitted by both monoexponential and biexponential models as described in the next paragraph. Then, the signal intensity was plotted in logarithmic scale versus the b values. Any observed nonlinear behavior was recorded, and the ADC obtained with b=0 and 1000 was

compared to that obtained with b=0 and 2000.

### B. Mathematical Models

#### 1. Monoexponential:

$$S = S_0 \exp(-bD)$$

where D is the ADC,  $S_0$  and S are the signal intensity without and with diffusion weight respectively. This model assumes monoexponential decaying behavior with the increase of b values.

#### 2. Biexponential: Since the fiber orientation in brain tissue is complicated, the overall diffusion behavior of a region can be regarded as the contribution of several compartments determined by the fiber tracts. In biexponential model, we divided water diffusion into two components.

$$S = S_0 [f_1 \exp(-bD_1) + f_2 \exp(-bD_2)]$$

$$f_1 + f_2 = 1$$

where  $f_1$  is the fraction of primary component, i.e. the fraction of principle orientation of fibers enclosed,  $D_1$  is the primary ADC,  $f_2$  is the fraction of residual component and  $D_2$  is the mean ADC contributed by other minor diffusion compartments.

### C. SNR simulation

To assess the influence of noise, simulated DWIs, superimposed with Gaussian noise, were generated with signal-to-noise ratio (SNR) 6, 4.5 and 2. Referring to the literature ADC range of human brain tissues, D was assigned 0.001 mm<sup>2</sup>/sec in monoexponential model while  $D_1$  and  $D_2$  were given 0.001 mm<sup>2</sup>/sec and 0.0001 mm<sup>2</sup>/sec respectively in biexponential model.

### D. Curve fitting

Least-squares algorithm was adopted to find D,  $D_1$ ,  $D_2$ ,  $f_1$  and  $f_2$ .  $R^2$  was calculated, where R is the multiple correlation coefficient. In different regions of the brain, the fitted ADCs were compared with the literature values. There must be discrepancies because more than one diffusion compartments were considered here. However, it is rational to use the literature CSF ADC (2.94±0.05 (x10<sup>-3</sup> mm<sup>2</sup>/sec)) as the upper limit of the ADCs obtained in other brain tissues. Moreover, we excluded any fitted ADC exceeding 1.5 times the literature value of the tissue.

## III. RESULTS

Fig.1 and Fig.2 show the result of simulation. In both mono- and bi- exponential models, noise plays an

## Report Documentation Page

<b>Report Date</b> 25 Oct 2001	<b>Report Type</b> N/A	<b>Dates Covered (from... to)</b> -
<b>Title and Subtitle</b> Multi-Component Decaying Behavior on High-b-Value Diffusion-weighted MRI		<b>Contract Number</b>
		<b>Grant Number</b>
		<b>Program Element Number</b>
<b>Author(s)</b>	<b>Project Number</b>	
	<b>Task Number</b>	
	<b>Work Unit Number</b>	
<b>Performing Organization Name(s) and Address(es)</b> Department of Electrical Engineering National Taiwan University Taipei, Taiwan		<b>Performing Organization Report Number</b>
<b>Sponsoring/Monitoring Agency Name(s) and Address(es)</b> US Army Research, Development & Standardization Group (UK) PSC 802 Box 15 FPO AE 09499-1500		<b>Sponsor/Monitor's Acronym(s)</b>
		<b>Sponsor/Monitor's Report Number(s)</b>
<b>Distribution/Availability Statement</b> Approved for public release, distribution unlimited		
<b>Supplementary Notes</b> Papers from 23rd Annual International Conference of the IEEE Engineering in Medicine and Biology Society, October 25-28, 2001, held in Istanbul, Turkey. See also ADM001351 for entire conference on cd-rom. , The original document contains color images.		
<b>Abstract</b>		
<b>Subject Terms</b>		
<b>Report Classification</b> unclassified	<b>Classification of this page</b> unclassified	
<b>Classification of Abstract</b> unclassified	<b>Limitation of Abstract</b> UU	
<b>Number of Pages</b> 3		

important role as  $b$  value exceeds 2500. In addition, when SNR drops to 2 (2.5 actually) or less, the simulated result begins to deviate from the ideal condition and this may lead to misinterpretation of mono- or multi- exponential decay.

The anatomical regions of interest are shown in Fig.3. Fig.4 shows the signal intensities of the diffusion-weighted images in cortex gray matter, corpus callosum and optical radiation, plotted in logarithmic scale versus the  $b$  values. The cortex gray matter and cerebrospinal fluid (not shown here) exhibited single exponential decaying characteristics. In the white matter, however, variant behaviors were found in different regions. It is seen that the corpus callosum and optical radiation, where there exist complicated neural fiber orientations within the chosen regions of interest, demonstrated non-linear multi-exponential decaying compartments along some directions. In the corpus callosum for example, ADC calculated from  $b=0$  and 1000 (along left-right direction) was higher than that obtained with  $b=0$  and 2000 by a factor of 2.

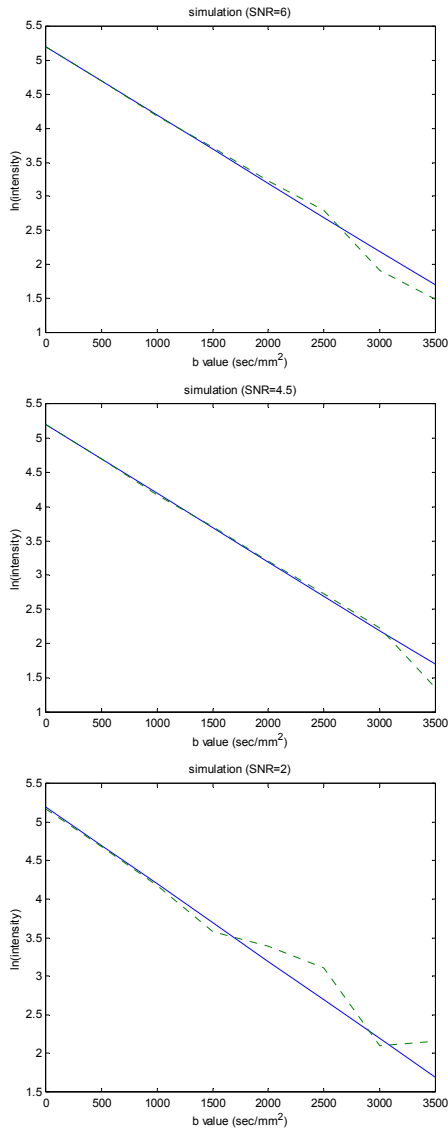


Fig. 1. Assessment of noise interference in curve-fitting in mono-exponential model ( $D = 0.001 \text{ mm}^2/\text{sec}$ ). Simulated DWIs superimposed by Gaussian noise were generated with SNR 6 (upper), 4.5 (middle) and 2 (lower) respectively. The signal intensity was plotted in logarithmic scale versus the  $b$  values. Solid line is the ideal mono-decay and dotted line is

obtained from simulation.

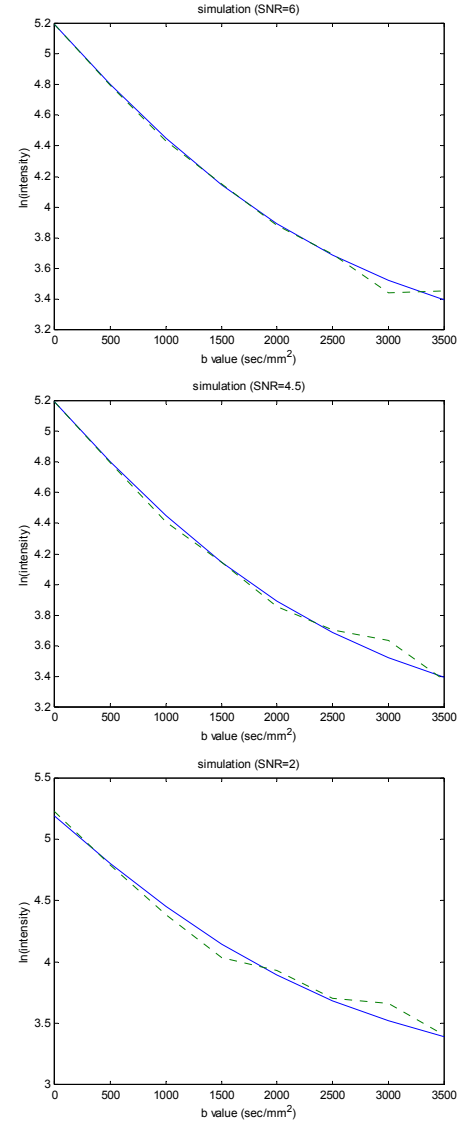


Fig. 2. Assessment of noise interference in curve-fitting in biexponential model ( $D_1 = 0.001 \text{ mm}^2/\text{sec}$ ,  $D_2 = 0.0001 \text{ mm}^2/\text{sec}$ ). Simulated DWIs superimposed by Gaussian noise were generated with SNR 6 (upper), 4.5 (middle) and 2 (lower) respectively. The signal intensity was plotted in logarithmic scale versus the  $b$  values. Solid line is the ideal biexponential decay and dotted line is obtained from simulation.

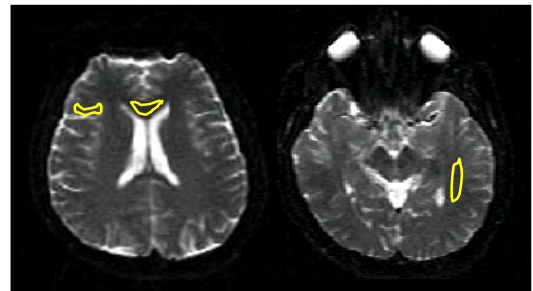


Fig. 3. The anatomical regions of interest: (a) cortex gray matter, (b) corpus callosum and (c) optical radiation.

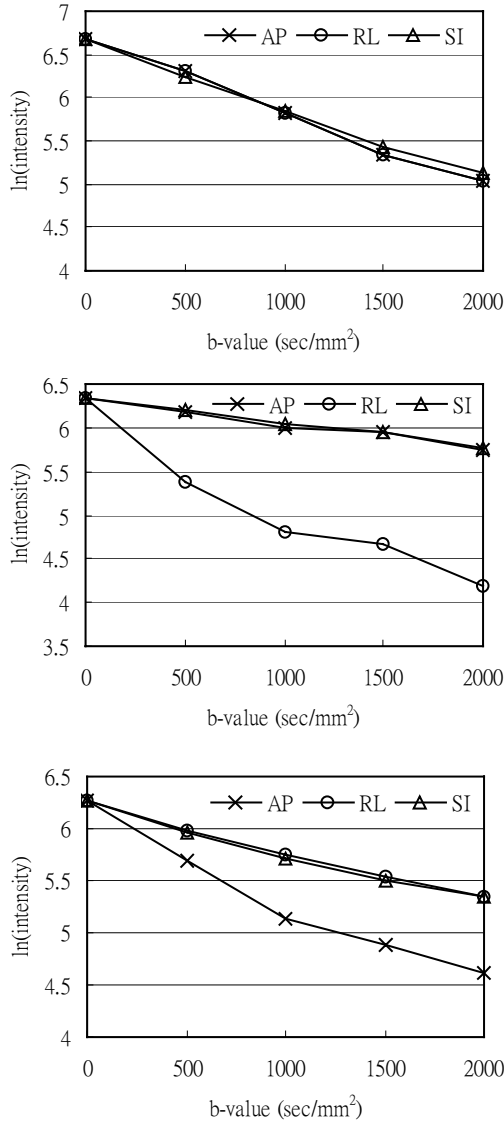


Fig. 4. The DWI signal intensities in cortex gray matter (upper), corpus callosum (middle) and optical radiation (lower) are plotted in logarithmic scale versus their corresponding b values. Diffusion-weighted gradients were applied along three orthogonal directions: antero-posterior (AP), right-left (RL) and superio-inferior (SI).

#### IV. DISCUSSIONS AND CONCLUSIONS

Diffusion is known to be anisotropic, with the preferential direction of movement along the white matter track (i.e., highest ADC). We thus attribute the multi-exponential behavior as arising from an inclusion of neural fibers along different orientations in a single region of interest. In cortex gray matter consisting of cell bodies, no noticeable multiple diffusion compartments (fiber tracts) exist. Hence, diffusion-induced signal decay is contributed by only one component, i.e. monoexponential or linear in logarithmic scale. In areas such as the corpus callosum where the fiber directions are complicated, DWI with low b values presumably reflects the fastest decaying component (i.e., fibers along the direction of diffusion-sensitizing gradients). Therefore, the existence of slow ADC compartments can only be visible on DWI with high b

values. The findings from this study further suggest that the interpretation of white matter track should be taken with care if mapping of the diffusion tensor were accomplished with only low b values.

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